

# 1. Introduction

This report presents estimates by the United States government of U.S. anthropogenic greenhouse gas emissions and sinks for the years 1990 through 1998. A summary of these estimates is provided in Table 1-4 and Table 1-5 by gas and source category. The emission estimates in these tables are presented on both a full molecular mass basis and on a Global Warming Potential (GWP) weighted basis in order to show the relative contribution of each gas to global average radiative forcing.<sup>1,2</sup> This report also discusses the methods and data used to calculate these emission estimates.

In June of 1992, the United States signed the United Nations Framework Convention on Climate Change (UNFCCC). The objective of the UNFCCC is “to achieve...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.”<sup>3,4</sup>

Parties to the Convention, by signing, make commitments “to develop, periodically update, publish and make available...national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies...”<sup>5</sup> The United States views this report as an opportunity to fulfill this commitment under UNFCCC.

In 1988, preceding the creation of the UNFCCC, the Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The charter of the IPCC is to assess available scientific information on climate change, assess the environmental and socio-economic impacts of climate change, and formulate response strategies (IPCC 1996). Under Working Group 1 of the IPCC, nearly 140 scientists and national experts from more than thirty countries corroborated in the creation of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) to ensure that the emission inventories submitted to the UNFCCC are consistent and comparable between nations. The *Revised 1996 IPCC Guidelines* were accepted by the IPCC at its Twelfth Session (Mexico City, 11-13 September 1996). The information provided in this inventory is presented in accordance with these guidelines.

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<sup>1</sup> See the section below entitled *Global Warming Potentials* for an explanation of GWP values.

<sup>2</sup> See the section below entitled *What is Climate Change?* for an explanation of radiative forcing.

<sup>3</sup> The term “anthropogenic”, in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC/UNEP/OECD/IEA 1997).

<sup>4</sup> Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change. See <<http://www.unfccc.de>>.

<sup>5</sup> Article 4 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change (also identified in Article 12). See <<http://www.unfccc.de>>.

Additionally, in order to fully comply with the *Revised 1996 IPCC Guidelines*, the United States has provided estimates of carbon dioxide emissions from fossil fuel combustion using the IPCC Reference Approach in Annex O.

Overall, the purpose of an inventory of anthropogenic greenhouse gas emissions is (1) to provide a basis for the ongoing development of methodologies for estimating sources and sinks of greenhouse gases; (2) to provide a common and consistent mechanism through which Parties to the UNFCCC can estimate emissions and compare the relative contribution of individual sources, gases, and nations to climate change; and (3) as a prerequisite for accounting for reductions and evaluating possible mitigation strategies.

## What is Climate Change?

Climate change refers to long-term fluctuations in temperature, precipitation, wind, and other elements of the Earth's climate system.<sup>6</sup> Natural processes such as solar-irradiance variations, variations in the Earth's orbital parameters,<sup>7</sup> and volcanic activity can produce variations in climate. The climate system can also be influenced by changes in the concentration of various gases in the atmosphere, which affect the Earth's absorption of radiation.

The Earth naturally absorbs and reflects incoming solar radiation and emits longer wavelength terrestrial (thermal) radiation back into space. On average, the absorbed solar radiation is balanced by the outgoing terrestrial radiation emitted to space. A portion of this terrestrial radiation, though, is itself absorbed by gases in the atmosphere. The energy from this absorbed terrestrial radiation warms the Earth's surface and atmosphere, creating what is known as the "natural greenhouse effect." Without the natural heat-trapping properties of these atmospheric gases, the average surface temperature of the Earth would be about 34°C lower (IPCC 1996).

Under the UNFCCC, the definition of climate change is "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods."<sup>8</sup> Given that definition, in its 1995 assessment of the science of climate change, the IPCC concluded that:

*Human activities are changing the atmospheric concentrations and distributions of greenhouse gases and aerosols. These changes can produce a radiative forcing by changing either the reflection or absorption of solar radiation, or the emission and absorption of terrestrial radiation (IPCC 1996).*

The IPCC went on to report in its assessment that the "[g]lobal mean surface temperature [of the Earth] has increased by between about 0.3 and 0.6 °C since the late 19<sup>th</sup> century..." (IPCC 1996) and finally concluded with the following statement:

*Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability, and because there are uncertainties in key factors. These include the magnitude and patterns of long term natural variability and the time-evolving pattern of forcing by, and response to, changes in concentrations of greenhouse gases and aerosols, and land surface changes. Nevertheless, the balance of the evidence suggests that there is a discernable human influence on global climate (IPCC 1996).*

## Greenhouse Gases

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide, and other trace gases in the atmosphere that absorb the terrestrial radiation leav-

<sup>6</sup> The Earth's climate system comprises the atmosphere, oceans, biosphere, cryosphere, and geosphere.

<sup>7</sup> For example, eccentricity, precession, and inclination.

<sup>8</sup> Article 1 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change.

ing the surface of the Earth (IPCC 1996). Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the atmosphere, space, land, and the oceans. A gauge of these changes is called radiative forcing, which is a simple measure of changes in the energy available to the Earth-atmosphere system (IPCC 1996). Holding everything else constant, increases in greenhouse gas concentrations in the atmosphere will produce positive radiative forcing (i.e., a net increase in the absorption of energy by the Earth).

*Climate change can be driven by changes in the atmospheric concentrations of a number of radiatively active gases and aerosols. We have clear evidence that human activities have affected concentrations, distributions and life cycles of these gases (IPCC 1996).*

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and ozone (O<sub>3</sub>). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, emitted solely by human activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as halons. Other fluorine containing halogenated substances include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF<sub>6</sub>). There are also several gases that, although they do not have a direct radiative forcing effect, do influence the formation and destruction of ozone, which does have such a terrestrial radiation absorbing effect. These gases referred to here as ozone precursors include carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), and nonmethane volatile organic compounds (NMVOCs).<sup>9</sup> Aerosols extremely small particles or liquid droplets often produced by emissions of sulfur dioxide (SO<sub>2</sub>) can also affect the absorptive characteristics of the atmosphere.

Carbon dioxide, methane, and nitrous oxide are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic

activities, however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes except when directly or indirectly perturbed out of equilibrium by anthropogenic activities generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems.

A brief description of each greenhouse gas, its sources, and its role in the atmosphere is given below. The following section then explains the concept of Global Warming Potentials (GWPs), which are assigned to individual gases as a measure of their relative average global radiative forcing effect.

*Water Vapor (H<sub>2</sub>O).* Overall, the most abundant and dominant greenhouse gas in the atmosphere is water vapor. Water vapor is neither long-lived nor well mixed in the atmosphere, varying spatially from 0 to 2 percent (IPCC 1996). In addition, atmospheric water can exist in several physical states including gaseous, liquid, and solid. Human activities are not believed to directly affect the average global concentration of water vapor; however, the radiative forcing produced by the increased concentrations of other greenhouse gases may indirectly affect the hydrologic cycle. A warmer atmosphere has an increased water holding capacity; yet, increased concentrations of water vapor affects the formation of clouds, which can both absorb and reflect solar and terrestrial radiation. Aircraft contrails, which consist of water vapor and other aircraft emittants, are similar to clouds in their radiative forcing effects (IPCC 1999).

*Carbon Dioxide (CO<sub>2</sub>).* In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and

<sup>9</sup> Also referred to in the U.S. Clean Air Act as “criteria pollutants.”

between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO<sub>2</sub>. Atmospheric carbon dioxide is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere, as of 1994, increased from approximately 280 parts per million by volume (ppmv) in pre-industrial<sup>10</sup> times to 358 ppmv, a 28 percent increase (IPCC 1996).<sup>11</sup> The IPCC has stated that “[t]here is no doubt that this increase is largely due to human activities, in particular fossil fuel combustion...” (IPCC 1996). Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of carbon dioxide.

In its latest scientific assessment, the IPCC also stated that “[t]he increased amount of carbon dioxide [in the atmosphere] is leading to climate change and will produce, on average, a global warming of the Earth’s surface because of its enhanced greenhouse effect although the magnitude and significance of the effects are not fully resolved” (IPCC 1996).

*Methane (CH<sub>4</sub>).* Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH<sub>4</sub>, as does the decomposition of municipal solid wastes. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a by-product of coal mining and incomplete fossil fuel combustion. The average global concentration of methane in the atmosphere was 1,720 parts per billion by volume (ppbv) in 1994, a 145 percent increase from the pre-industrial concentration of 700 ppbv (IPCC 1996).

It is estimated that 60 to 80 percent of current CH<sub>4</sub> emissions are the result of anthropogenic activities. Carbon isotope measurements indicate that roughly 20 percent of methane emissions are from fossil fuel consumption, and an equal percentage is produced by natural wetlands, which will likely increase with rising temperatures and rising microbial action (IPCC 1996).

Methane is removed from the atmosphere by reacting with the hydroxyl radical (OH) and is ultimately converted to CO<sub>2</sub>. Increasing emissions of methane, though, reduces the concentration of OH, and thereby the rate of further methane removal (IPCC 1996).

*Nitrous Oxide (N<sub>2</sub>O).* Anthropogenic sources of N<sub>2</sub>O emissions include agricultural soils, especially the use of synthetic and manure fertilizers; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste combustion; and biomass burning. The atmospheric concentration of nitrous oxide (N<sub>2</sub>O) in 1994 was about 312 parts per billion by volume (ppbv), while pre-industrial concentrations were roughly 275 ppbv. The majority of this 13 percent increase has occurred after the pre-industrial period and is most likely due to anthropogenic activities (IPCC 1996). Nitrous oxide is removed from the atmosphere primarily by the photolytic action of sunlight in the stratosphere.

*Ozone (O<sub>3</sub>).* Ozone is present in both the upper stratosphere,<sup>12</sup> where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,<sup>13</sup> where it is the main component of anthropogenic photochemical “smog.” During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as chlorofluorocarbons (CFCs), have depleted stratospheric ozone concentrations. This loss of ozone in the strato-

<sup>10</sup> The pre-industrial period is considered as the time preceding the year 1750 (IPCC 1996).

<sup>11</sup> Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (i.e., 750-1750), a time of relative climate stability, fluctuated by about  $\pm 10$  ppmv around 280 ppmv (IPCC 1996).

<sup>12</sup> The stratosphere is the layer from the troposphere up to roughly 50 kilometers. In the lower regions the temperature is nearly constant but in the upper layer the temperature increases rapidly because of sunlight absorption by the ozone layer. The ozone-layer is the part of the stratosphere from 19 kilometers up to 48 kilometers where the concentration of ozone reaches up to 10 parts per million.

<sup>13</sup> The troposphere is the layer from the ground up to 11 kilometers near the poles and up to 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere where people live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for most weather processes, including most of the water vapor and clouds.

sphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 1996).

Tropospheric ozone, which is also a greenhouse gas, is produced from the oxidation of methane and from reactions with precursor gases such as carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), and non-methane volatile organic compounds (NMVOCs). This latter group of ozone precursors is included in the category referred to as “criteria pollutants” in the United States under the Clean Air Act<sup>14</sup> and its subsequent amendments. The tropospheric concentrations of both ozone and these precursor gases are short-lived and, therefore, spatially variable.

*Halocarbons, Perfluorocarbons, and Sulfur Hexafluoride (SF<sub>6</sub>).* Halocarbons are, for the most part, man-made chemicals that have both direct and indirect radiative forcing effects. Halocarbons that contain chlorine chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl chloroform, and carbon tetrachloride and bromine halons, methyl bromide, and hydrobromofluorocarbons (HBFCs) result in stratospheric ozone depletion and are therefore controlled under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. Although CFCs and HCFCs include potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which is itself an important greenhouse gas in addition to shielding the Earth from harmful levels of ultraviolet radiation. Under the *Montreal Protocol*, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the *Protocol*, a cap was placed on the production and importation of HCFCs by non-Article 5<sup>15</sup> countries beginning in 1996, and then followed by a complete phase-out by the year 2030. The ozone depleting gases covered under the *Montreal*

*Protocol* and its Amendments are not covered by the UNFCCC; however, they are reported in this inventory under Annex L.

Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF<sub>6</sub>) are not ozone depleting substances, and therefore are not covered under the *Montreal Protocol*. They are, however, powerful greenhouse gases. HFCs primarily used as replacements for ozone depleting substances but also emitted as a by-product of the HCFC-22 manufacturing process currently have a small aggregate radiative forcing impact; however, it is anticipated that their contribution to overall radiative forcing will increase (IPCC 1996). PFCs and SF<sub>6</sub> are predominantly emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. Currently, the radiative forcing impact of PFCs, and SF<sub>6</sub> is also small; however, because they have extremely long atmospheric lifetimes, their concentrations tend to irreversibly accumulate in the atmosphere.

*Carbon Monoxide (CO).* Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH<sub>4</sub> and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical) that would otherwise assist in destroying CH<sub>4</sub> and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO<sub>2</sub>. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.

*Nitrogen Oxides (NO<sub>x</sub>).* The primary climate change effects of nitrogen oxides (i.e., NO and NO<sub>2</sub>) are indirect and result from their role in promoting the formation of ozone in the troposphere and, to a lesser degree, lower stratosphere, where it has positive radiative forcing effects. (NO<sub>x</sub> emissions injected higher in the stratosphere<sup>16</sup> can lead to stratospheric ozone deple-

<sup>14</sup> [42 U.S.C §7408, CAA §108]

<sup>15</sup> Article 5 of the *Montreal Protocol* covers several groups of countries, especially developing countries, with low consumption rates of ozone depleting substances. Developing countries with per capita consumption of less than 0.3 kg of certain ozone depleting substances (weighted by their ozone depleting potential) receive financial assistance and a grace period of ten additional years in the phase-out of ozone depleting substances.

<sup>16</sup> Primarily from fuel combustion emissions from high altitude supersonic aircraft.

tion.) Additionally, NO<sub>x</sub> emissions from aircraft are expected to decrease methane concentrations, thus having a negative radiative forcing effect (IPCC 1999). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning—both natural and anthropogenic fires—fuel combustion, and, in the stratosphere, from nitrous oxide (N<sub>2</sub>O). Concentrations of NO<sub>x</sub> are both relatively short-lived in the atmosphere and spatially variable.

*Nonmethane Volatile Organic Compounds (NMVOCs).* Nonmethane volatile organic compounds include compounds such as propane, butane, and ethane. These compounds participate, along with NO<sub>x</sub>, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents. Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

*Aerosols.* Aerosols are extremely small particles or liquid droplets found in the atmosphere. They can be produced by natural events such as dust storms and volcanic activity or by anthropogenic processes such as fuel combustion. Their effect upon radiative forcing is to both absorb radiation and to alter cloud formation, thereby affecting the reflectivity (i.e., albedo) of the Earth. Aerosols are removed from the atmosphere primarily by precipitation, and generally have short atmospheric lifetimes. Like ozone precursors, aerosol concentrations and composition vary by region (IPCC 1996).

Anthropogenic aerosols in the troposphere are primarily the result of sulfur dioxide (SO<sub>2</sub>)<sup>17</sup> emissions from fossil fuel and biomass burning. Overall, aerosols tend to produce a negative radiative forcing effect (i.e., net cooling effect on the climate), although because they are short-lived in the atmosphere lasting days to weeks their concentrations respond rapidly to changes in emissions.<sup>18</sup> Locally, the negative radiative forcing effects of aerosols can offset the positive forcing of greenhouse gases (IPCC 1996). “However, the aerosol effects do not

cancel the global-scale effects of the much longer-lived greenhouse gases, and significant climate changes can still result” (IPCC 1996). Emission estimates for sulfur dioxide are provided in Annex M of this report.

## Global Warming Potentials

A Global Warming Potential (GWP) is intended as a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas (see Table 1-1). It is defined as the cumulative radiative forcing both direct and indirect effects over a specified time horizon resulting from the emission of a unit mass of gas relative to some reference gas (IPCC 1996). Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformations involving the original gas produces a gas or gases that are greenhouse gases, or when a gas influences the atmospheric lifetimes of other gases. The reference gas used is CO<sub>2</sub>, and therefore GWP weighted emissions are measured in million metric tons of carbon equivalents (MMTCE). Carbon comprises 12/44<sup>th</sup> of carbon dioxide by weight. The relationship between gigagrams (Gg) of a gas and MMTCE can be expressed as follows:

$$\text{MMTCE} = (\text{Gg of gas}) \times \left( \frac{\text{MMT}}{1,000 \text{ Gg}} \right) \times (\text{GWP}) \times \left( \frac{12}{44} \right)$$

where,

MMTCE = Million Metric Tons of Carbon Equivalents

Gg = Gigagrams (equivalent to a thousand metric tons)

GWP = Global Warming Potential

$\left( \frac{12}{44} \right)$  = Carbon to carbon dioxide molecular weight ratio.

MMT = Million Metric Tons

GWP values allow policy makers to compare the impacts of emissions and reductions of different gases.

<sup>17</sup> Sulfur dioxide is a primary anthropogenic contributor to the formation of “acid rain” and other forms of atmospheric acid deposition.

<sup>18</sup> Volcanic activity can inject significant quantities of aerosol producing sulfur dioxide and other sulfur compounds into the stratosphere, which can result in a longer negative forcing effect (i.e., a few years) (IPCC 1996).

According to the IPCC, GWPs typically have an uncertainty of  $\pm 35$  percent. The parties to the UNFCCC have also agreed to use GWPs based upon a 100 year time horizon although other time horizon values are available.

*In addition to communicating emissions in units of mass, Parties may choose also to use global warming potentials (GWPs) to reflect their inventories and projections in carbon dioxide-equivalent terms, using information provided by the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report. Any use of GWPs should be based on the effects of the greenhouse gases over a 100-year time horizon. In addition, Parties may also use other time horizons.<sup>19</sup>*

Greenhouse gases with long atmospheric lifetimes (e.g., CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFCs, PFCs, and SF<sub>6</sub>) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, tropospheric ozone, ozone precursors (e.g., NO<sub>x</sub>, CO, and NMVOCs), and tropospheric aerosols (e.g., SO<sub>2</sub> products), however, vary regionally, and consequently it is difficult to quantify their global radiative forcing impacts. No GWP values are attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere. Other greenhouse gases not yet listed by the Intergovernmental Panel on Climate Change (IPCC), but are already or soon will be in commercial use include: HFC-245fa, hydrofluoroethers (HFEs), and nitrogen trifluoride (NF<sub>3</sub>).

## Recent Trends in U.S. Greenhouse Gas Emissions

Total U.S. greenhouse gas emissions rose in 1998 to 1,834.6 million metric tons of carbon equivalents (MMTCE)<sup>20</sup> (11.2 percent above 1990 baseline levels).

**Table 1-1: Global Warming Potentials and Atmospheric Lifetimes (Years)**

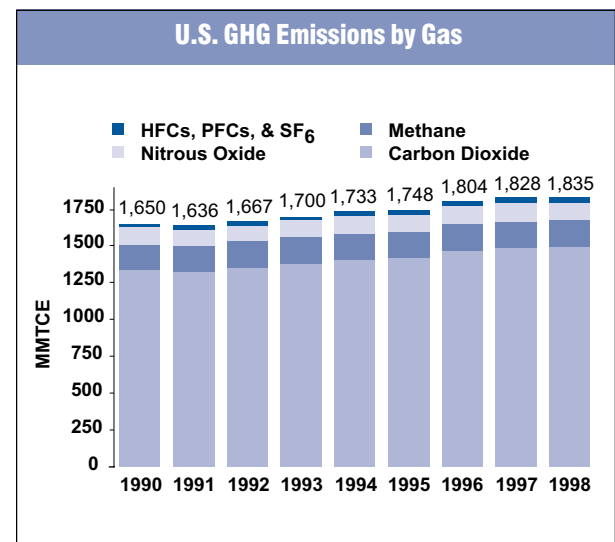
Gas	Atmospheric Lifetime	GWP <sup>a</sup>
Carbon dioxide (CO <sub>2</sub> )	50-200	1
Methane (CH <sub>4</sub> ) <sup>b</sup>	12 $\pm$ 3	21
Nitrous oxide (N <sub>2</sub> O)	120	310
HFC-23	264	11,700
HFC-125	32.6	2,800
HFC-134a	14.6	1,300
HFC-143a	48.3	3,800
HFC-152a	1.5	140
HFC-227ea	36.5	2,900
HFC-236fa	209	6,300
HFC-4310mee	17.1	1,300
CF <sub>4</sub>	50,000	6,500
C <sub>2</sub> F <sub>6</sub>	10,000	9,200
C <sub>4</sub> F <sub>10</sub>	2,600	7,000
C <sub>6</sub> F <sub>14</sub>	3,200	7,400
SF <sub>6</sub>	3,200	23,900

Source: (IPCC 1996)

<sup>a</sup> 100 year time horizon

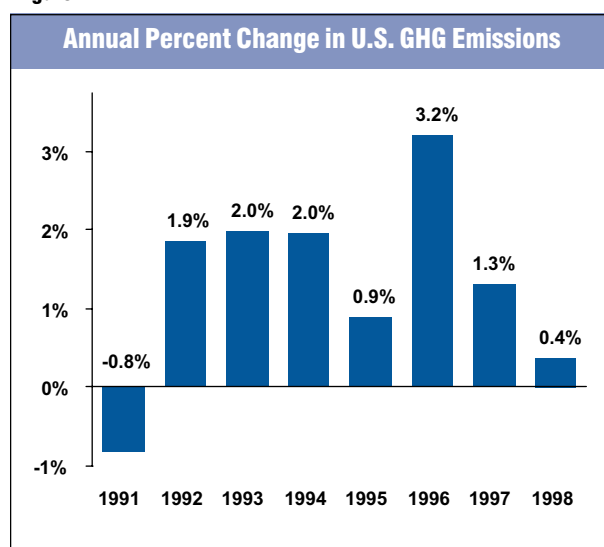
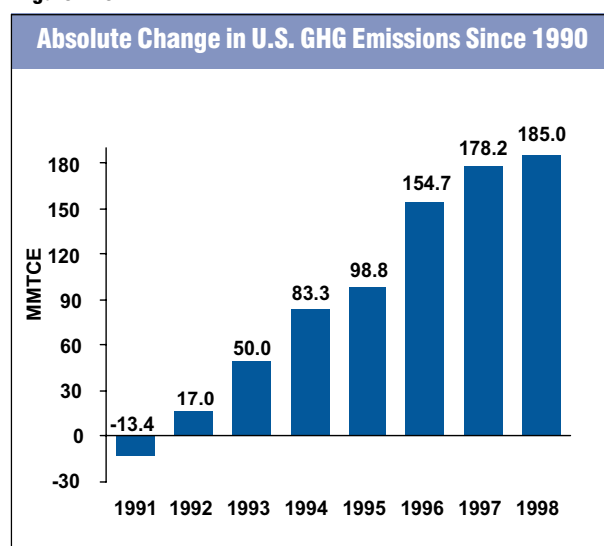
<sup>b</sup> The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO<sub>2</sub> is not included.

**Figure 1-1**



<sup>19</sup> Framework Convention on Climate Change; FCCC/CP/1996/15/Add.1; 29 October 1996; Report of the Conference of the Parties at its second session; held at Geneva from 8 to 19 July 1996; Addendum; Part Two: Action taken by the Conference of the Parties at its second session; Decision 9/CP.2; Communications from Parties included in Annex I to the Convention: guidelines, schedule and process for consideration; Annex: Revised Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention; p. 18.

<sup>20</sup> Estimates are presented in units of millions of metric tons of carbon equivalents (MMTCE), which weights each gas by its GWP value, or Global Warming Potential (see previous section).

**Figure 1-2****Figure 1-3**

The single year increase in emissions from 1997 to 1998 was 0.4 percent (6.8 MMTCE), less than the 1.3 percent average annual rate of increase for the 1990s. Figure 1-1 through Figure 1-3 illustrate the overall trends in total U.S. emissions by gas, annual changes, and absolute changes since 1990.

As the largest source of U.S. greenhouse gas emissions, CO<sub>2</sub> from fossil fuel combustion, accounted for 80 percent of weighted emissions in 1998. Emissions from this source grew by 11 percent (148.1 MMTCE) from 1990 to 1998 and were also responsible for over 80 percent of the increase in national emissions during this period. The annual increase in CO<sub>2</sub> emissions from this

source was only 0.5 percent in 1998 lower than the source's average annual rate of 1.3 percent during the 1990s despite a strong 3.9 percent increase in U.S. gross domestic product.

In addition to economic growth, changes in CO<sub>2</sub> emission from fossil fuel combustion are also correlated with energy prices and seasonal temperatures. Exceptionally mild winter conditions in 1998 moderated growth in CO<sub>2</sub> emissions from fossil fuel combustion below what would have been expected given the strength of the economy and continued low fuel prices. Table 1-2 shows annual changes in emissions during the last few years of the 1990s for particular fuel types and sectors.

Carbon dioxide emissions from fossil fuel combustion increased dramatically in 1996, due primarily to two factors: 1) fuel switching by electric utilities from natural gas to more carbon intensive coal as to colder winter conditions and the associated rise in demand for natural gas from residential, commercial and industrial customers for heating caused gas prices to rise sharply; and 2) higher consumption of petroleum fuels for transportation. Milder weather conditions in summer and winter moderated the growth in emissions in 1997; however, the shut-down of several nuclear power plants lead electric utilities to increase their consumption of coal to offset the lost capacity. In 1998, weather conditions were a dominant factor in slowing the growth in emissions. Warm winter temperatures resulted in a significant drop in residential, commercial, and industrial natural gas consumption. This drop in emissions from natural gas used for heating was primarily offset by two factors: 1) electric utility emissions, which increased in part due to a hot summer and its associated air conditioning demand; and 2) increased motor gasoline consumption for transportation.

Other significant trends in emissions from additional source categories over the nine year period from 1990 through 1998 included the following:

- Aggregate HFC and PFC emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) increased by 14.2 MMTCE. This increase was partly offset, however, by reductions in PFC emissions from aluminum production by 2.6 MMTCE (48 percent), which were the result of both

**Table 1-2: Annual Change in CO<sub>2</sub> Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (MMTCE and Percent)**

Sector	Fuel Type	1995-1996		1996-1997		1997-1998	
Electric Utility	Coal	24.5	5.7%	14.3	3.1%	5.5	1.2%
Electric Utility	Petroleum	1.4	10.0%	2.2	14.4%	7.3	41.6%
Electric Utility	Natural Gas	(6.9)	(14.6%)	3.3	8.1%	4.2	9.8%
Transportation <sup>a</sup>	Petroleum	13.8	3.3%	1.1	0.2%	7.2	1.7%
Residential	Natural Gas	5.8	8.1%	(3.8)	(4.9%)	(7.4)	(10.0%)
Commercial	Natural Gas	1.9	4.2%	0.9	1.9%	(2.7)	(5.7%)
Industrial	Natural Gas	4.7	3.4%	(1.4)	(1.0%)	(2.9)	(2.0%)
All Sectors <sup>b</sup>	All Fuels <sup>b</sup>	49.4	3.5%	19.4	1.3%	7.5	0.5%

<sup>a</sup> Excludes emissions from International Bunker Fuels.

<sup>b</sup> Includes fuels and sectors not shown in table.

voluntary industry emission reduction efforts and lower domestic aluminum production.

- Combined N<sub>2</sub>O and CH<sub>4</sub> emissions from mobile combustion rose by 3.3 MMTCE (22 percent), primarily due to increased rates of N<sub>2</sub>O generation in highway vehicles.
- Methane emissions from the manure management activities have increased by 7.9 MMTCE (53 percent) as the composition of the swine and dairy industries shift toward larger facilities. An increased number of large facilities leads to an increased use of liquid systems, which translates into increased methane production.
- Methane emissions from coal mining dropped by 6.2 MMTCE (26 percent) as a result of the mining of less gassy coal from underground mines and the increased use of methane from degasification systems.
- Nitrous oxide emissions from agricultural soil management increased by 8.5 MMTCE (11 percent) as fertilizer consumption and cultivation of nitrogen fixing crops rose.
- By 1998, all of the three major adipic acid producing plants had voluntarily implemented N<sub>2</sub>O abatement technology; as a result, emissions fell by 3.0 MMTCE (60 percent). The majority of this decline occurred from 1997 to 1998, despite increased production.

Overall, from 1990 to 1998, total emissions of CO<sub>2</sub>,

CH<sub>4</sub>, and N<sub>2</sub>O increased by 153.7 (11 percent), 3.1 (2 percent), and 11.1 MMTCE (10 percent), respectively. During the same period, weighted emissions of HFCs, PFCs, and SF<sub>6</sub> rose by 17.0 MMTCE (73 percent). Despite being emitted in smaller quantities relative to the other principle greenhouse gases, emissions of HFCs, PFCs, and SF<sub>6</sub> are significant because of their extremely high Global Warming Potentials and, in the cases of PFCs and SF<sub>6</sub>, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon sequestration in forests and in landfilled carbon, which were estimated to be 12 percent of total emissions in 1998.

As an alternative, emissions can be aggregated across gases by the IPCC defined sectors, referred to here as chapters. Over the nine year period of 1990 to 1998, total emissions in the Energy, Industrial Processes, Agriculture, and Waste chapters climbed by 146.5 (10 percent), 18.5 (39 percent), 18.5 (14 percent), and 1.5 MMTCE (2 percent), respectively. Estimates of the quantity of carbon sequestered in the Land-Use Change and Forestry chapter, although based on projections, declined by 105.5 MMTCE (33 percent).

Table 1-4 summarizes emissions and sinks from all U.S. anthropogenic sources in weighted units of MMTCE, while unweighted gas emissions and sinks in gigagrams (Gg) are provided in Table 1-5. Alternatively, emissions and sinks are aggregated by chapter in Table

## Box 1-1: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data

There are several ways to assess a nation's greenhouse gas emitting intensity. These measures of intensity could be based on aggregate energy consumption because energy-related activities<sup>21</sup> are the largest sources of emissions, on fossil fuel consumption only because almost all energy-related emissions involve the combustion of fossil fuels, on electricity consumption because electric utilities were the largest sources of U.S. greenhouse gas emissions in 1998, on total gross domestic product as a measure of national economic activity, or on a per capita basis. Depending upon which of these measures is used, the United States could appear to have reduced or increased its national greenhouse gas intensity. Table 1-3 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. Greenhouse gas emissions in the U.S. have grown at an average annual rate of 1.3 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption thereby indicating an improved or lower greenhouse gas emitting intensity and much slower than that for either electricity consumption or overall gross domestic product. Emissions, however, are growing faster than national population, thereby indicating a worsening or higher greenhouse gas emitting intensity on a per capita basis (see Figure 1-4). Overall, atmospheric CO<sub>2</sub> concentrations a function of many complex anthropogenic and natural processes are increasing at 0.4 percent per year.

**Table 1-3: Recent Trends in Various U.S. Data (Index 1990 = 100)**

Variable Rate <sup>g</sup>	1991	1992	1993	1994	1995	1996	1997	1998	Growth
GHG Emissions <sup>a</sup>	99	101	103	105	106	109	111	111	1.3%
Energy Consumption <sup>b</sup>	100	101	104	106	108	112	112	112	1.4%
Fossil Fuel Consumption <sup>c</sup>	99	101	103	105	106	110	111	111	1.4%
Electricity Consumption <sup>c</sup>	102	102	105	108	111	114	116	119	2.2%
GDP <sup>d</sup>	99	102	104	108	110	114	118	123	2.6%
Population <sup>e</sup>	101	102	103	104	105	106	107	108	1.0%
Atmospheric CO <sub>2</sub> Concentration <sup>f</sup>	100	101	101	101	102	102	103	104	0.4%

<sup>a</sup> GWP weighted values

<sup>b</sup> Energy content weighted values. (DOE/EIA)

<sup>c</sup> (DOE/EIA)

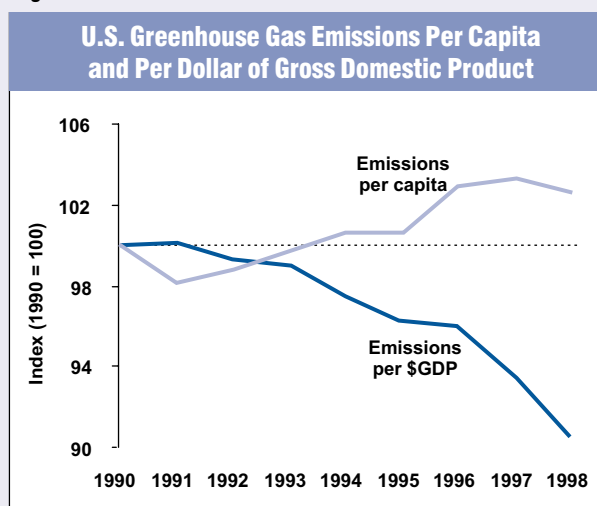
<sup>d</sup> Gross Domestic Product in chained 1992 dollars (BEA 1999)

<sup>e</sup> (U.S. Census Bureau 1999)

<sup>f</sup> Mauna Loa Observatory, Hawaii (Keeling and Whorf 1999)

<sup>g</sup> Average annual growth rate

**Figure 1-4**



<sup>21</sup> Energy-related activities are those that involve fossil fuel combustion (industrial, transportation, residential, and commercial end-use sectors), and the production, transmission, storage, and distribution of fossil fuels.

**Table 1-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMTCE)**

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
<b>CO<sub>2</sub></b>	<b>1,340.3</b>	<b>1,326.1</b>	<b>1,350.4</b>	<b>1,383.3</b>	<b>1,404.8</b>	<b>1,416.5</b>	<b>1,466.2</b>	<b>1,486.4</b>	<b>1,494.0</b>
Fossil Fuel Combustion	1,320.1	1,305.8	1,330.1	1,361.5	1,382.0	1,392.0	1,441.3	1,460.7	1,468.2
Cement Manufacture	9.1	8.9	8.9	9.4	9.8	10.0	10.1	10.5	10.7
Natural Gas Flaring	2.5	2.8	2.8	3.7	3.8	4.7	4.5	4.2	3.9
Lime Manufacture	3.0	3.0	3.1	3.1	3.2	3.4	3.6	3.7	3.7
Waste Combustion	2.8	3.0	3.0	3.1	3.1	3.0	3.1	3.4	3.5
Limestone and Dolomite Use	1.4	1.3	1.2	1.1	1.5	1.9	2.0	2.3	2.4
Soda Ash Manufacture and Consumption	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2
Carbon Dioxide Consumption	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4
Land-Use Change and Forestry (Sink) <sup>a</sup>	(316.4)	(316.3)	(316.2)	(212.7)	(212.3)	(211.8)	(211.3)	(211.1)	(210.8)
International Bunker Fuels <sup>b</sup>	32.2	32.7	30.0	27.2	26.7	27.5	27.9	29.9	31.3
<b>CH<sub>4</sub></b>	<b>177.9</b>	<b>177.7</b>	<b>179.4</b>	<b>178.7</b>	<b>181.6</b>	<b>184.1</b>	<b>183.1</b>	<b>183.8</b>	<b>180.9</b>
Landfills	58.2	58.1	59.1	59.6	59.9	60.5	60.2	60.2	58.8
Enteric Fermentation	32.7	32.8	33.2	33.7	34.5	34.9	34.5	34.2	33.7
Natural Gas Systems	33.0	33.4	33.9	34.6	34.3	34.0	34.6	34.1	33.6
Manure Management	15.0	15.5	16.0	17.1	18.8	19.7	20.4	22.1	22.9
Coal Mining	24.0	22.8	22.0	19.2	19.4	20.3	18.9	18.8	17.8
Petroleum Systems	7.4	7.5	7.2	6.9	6.7	6.7	6.5	6.5	6.3
Rice Cultivation	2.4	2.3	2.6	2.4	2.7	2.6	2.4	2.6	2.7
Stationary Sources	2.3	2.4	2.4	2.4	2.4	2.5	2.6	2.3	2.3
Mobile Sources	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.3
Wastewater Treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Petrochemical Production	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Agricultural Residue Burning	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2
Silicon Carbide Production	+	+	+	+	+	+	+	+	+
International Bunker Fuels <sup>b</sup>	+	+	+	+	+	+	+	+	+
<b>N<sub>2</sub>O</b>	<b>108.2</b>	<b>110.5</b>	<b>113.3</b>	<b>113.8</b>	<b>121.5</b>	<b>118.8</b>	<b>121.5</b>	<b>122.4</b>	<b>119.4</b>
Agricultural Soil Management	75.3	76.3	78.2	77.3	83.5	80.4	82.4	84.2	83.9
Mobile Sources	13.8	14.6	15.7	16.5	17.1	17.4	17.5	17.3	17.2
Nitric Acid	4.9	4.9	5.0	5.1	5.3	5.4	5.6	5.8	5.8
Stationary Sources	3.8	3.8	3.9	3.9	4.0	4.0	4.2	4.2	4.3
Manure Management	3.4	3.6	3.5	3.7	3.8	3.7	3.8	3.9	4.0
Human Sewage	2.0	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2
Adipic Acid	5.0	5.2	4.8	5.2	5.5	5.5	5.7	4.7	2.0
Agricultural Residue Burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
International Bunker Fuels <sup>b</sup>	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3
<b>HFCs, PFCs, and SF<sub>6</sub></b>	<b>23.3</b>	<b>22.0</b>	<b>23.5</b>	<b>23.8</b>	<b>25.1</b>	<b>29.0</b>	<b>33.5</b>	<b>35.3</b>	<b>40.3</b>
Substitution of Ozone Depleting Substances	0.3	0.2	0.4	1.4	2.7	7.0	9.9	12.3	14.5
HCFC-22 Production	9.5	8.4	9.5	8.7	8.6	7.4	8.5	8.2	10.9
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0	7.0	7.0
Magnesium Production and Processing	1.7	2.0	2.2	2.5	2.7	3.0	3.0	3.0	3.0
Aluminum Production	5.4	4.7	4.4	3.8	3.2	3.1	3.2	3.0	2.8
Semiconductor Manufacture	0.8	0.8	0.8	1.0	1.1	1.5	1.9	1.9	2.1
<b>Total Emissions</b>	<b>1,649.7</b>	<b>1,636.2</b>	<b>1,666.6</b>	<b>1,699.7</b>	<b>1,733.0</b>	<b>1,748.5</b>	<b>1,804.4</b>	<b>1,827.9</b>	<b>1,834.6</b>
<b>Net Emission (Sources and Sinks)</b>	<b>1,333.3</b>	<b>1,320.0</b>	<b>1,350.5</b>	<b>1,487.0</b>	<b>1,520.7</b>	<b>1,536.6</b>	<b>1,593.1</b>	<b>1,616.8</b>	<b>1,623.8</b>

+ Does not exceed 0.05 MMTCE

<sup>a</sup> Sinks are only included in net emissions total. Estimates of net carbon sequestration due to land-use change and forestry activities exclude non-forest soils, and are based partially upon projections of forest carbon stocks.<sup>b</sup> Emissions from International Bunker Fuels are not included in totals.

Note: Totals may not sum due to independent rounding.

**Table 1-5: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Gg)**

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
<b>CO<sub>2</sub></b>	<b>4,914,351</b>	<b>4,862,349</b>	<b>4,951,561</b>	<b>5,072,271</b>	<b>5,150,787</b>	<b>5,193,841</b>	<b>5,376,081</b>	<b>5,449,974</b>	<b>5,478,051</b>
Fossil Fuel Combustion	4,840,483	4,787,926	4,876,887	4,992,123	5,067,248	5,103,838	5,284,901	5,355,900	5,383,502
Cement Manufacture	33,278	32,535	32,792	34,624	36,087	36,847	37,079	38,323	39,227
Natural Gas Flaring	9,097	10,295	10,169	13,716	13,800	17,164	16,506	15,521	14,214
Lime Manufacture	11,092	10,891	11,245	11,496	11,895	12,624	13,179	13,434	13,627
Waste Combustion	10,345	10,931	10,993	11,295	11,308	11,104	11,504	12,532	12,889
Limestone and Dolomite Use	5,113	4,896	4,502	4,058	5,541	6,987	7,499	8,537	8,854
Soda Ash Manufacture and Consumption	4,144	4,035	4,091	4,048	4,012	4,309	4,273	4,434	4,325
Carbon Dioxide Consumption	800	840	882	912	898	968	1,140	1,294	1,413
Land-Use Change and Forestry (Sink) <sup>a</sup>	(1,159,994)	(1,159,646)	(1,159,299)	(779,935)	(778,285)	(776,659)	(774,725)	(774,083)	(773,019)
International Bunker Fuels <sup>b</sup>	117,965	120,019	109,965	99,886	98,017	101,014	102,197	109,788	114,700
<b>CH<sub>4</sub></b>	<b>31,054</b>	<b>31,020</b>	<b>31,329</b>	<b>31,203</b>	<b>31,711</b>	<b>32,147</b>	<b>31,972</b>	<b>32,084</b>	<b>31,593</b>
Landfills	10,171	10,152	10,321	10,402	10,452	10,566	10,508	10,510	10,268
Enteric Fermentation	5,712	5,732	5,804	5,876	6,016	6,094	6,032	5,973	5,885
Natural Gas Systems	5,770	5,840	5,923	6,042	5,987	5,931	6,041	5,961	5,860
Manure Management	2,613	2,708	2,801	2,990	3,283	3,447	3,567	3,861	3,990
Coal Mining	4,184	3,975	3,835	3,356	3,390	3,550	3,301	3,274	3,104
Petroleum Systems	1,294	1,307	1,262	1,206	1,175	1,168	1,143	1,142	1,108
Rice Cultivation	414	404	453	414	476	445	420	453	476
Stationary Sources	404	410	425	415	416	437	446	399	395
Mobile Sources	257	255	257	255	253	251	246	239	232
Wastewater Treatment	150	152	154	155	157	158	160	161	163
Petrochemical Production	56	57	60	66	70	72	75	77	77
Agricultural Residue Burning	30	28	33	26	34	28	32	34	35
Silicon Carbide Production	1	1	1	1	1	1	1	1	1
International Bunker Fuels <sup>b</sup>	2	2	2	2	2	2	2	2	2
<b>N<sub>2</sub>O</b>	<b>1,280</b>	<b>1,307</b>	<b>1,340</b>	<b>1,346</b>	<b>1,437</b>	<b>1,406</b>	<b>1,437</b>	<b>1,448</b>	<b>1,412</b>
Agricultural Soil Management	891	903	925	914	988	951	975	996	992
Mobile Sources	163	172	185	195	202	206	207	205	203
Nitric Acid	58	58	59	60	63	64	67	68	68
Stationary Source	45	45	46	46	47	48	49	50	50
Manure Management	40	42	42	43	44	44	45	46	47
Human Sewage	23	24	24	24	25	25	25	25	25
Adipic Acid	59	62	57	61	65	66	67	55	23
Agricultural Residue Burning	1	1	1	1	1	1	1	1	1
Waste Combustion	1	1	1	1	1	1	1	1	1
International Bunker Fuels <sup>b</sup>	3	3	3	3	3	3	3	3	3
<b>HFCs, PFCs, and SF<sub>6</sub></b>	<b>M</b>	<b>M</b>	<b>M</b>	<b>M</b>	<b>M</b>	<b>M</b>	<b>M</b>	<b>M</b>	<b>M</b>
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M	M	M
HCFC-22 Production <sup>c</sup>	3	3	3	3	3	2	3	3	3
Semiconductor Manufacture	M	M	M	M	M	M	M	M	M
Electrical Transmission and Distribution <sup>d</sup>	1	1	1	1	1	1	1	1	1
Magnesium Production and Processing <sup>d</sup>	+	+	+	+	+	+	+	+	+
<b>NO<sub>x</sub></b>	<b>21,798</b>	<b>21,936</b>	<b>22,176</b>	<b>22,398</b>	<b>22,683</b>	<b>22,177</b>	<b>22,034</b>	<b>22,153</b>	<b>22,066</b>
<b>CO</b>	<b>85,394</b>	<b>87,485</b>	<b>84,589</b>	<b>84,716</b>	<b>88,911</b>	<b>80,093</b>	<b>82,028</b>	<b>79,284</b>	<b>78,082</b>
<b>NMVOCS</b>	<b>18,795</b>	<b>18,929</b>	<b>18,527</b>	<b>18,708</b>	<b>19,290</b>	<b>18,613</b>	<b>17,624</b>	<b>17,469</b>	<b>17,011</b>

+ Does not exceed 0.5 Gg

M Mixture of multiple gases

NA Not Available

<sup>a</sup> Sinks are not included in CO<sub>2</sub> emissions total. Estimates of net carbon sequestration due to land-use change and forestry activities exclude non-forest soils, and are based partially upon projections of forest carbon stocks.

<sup>b</sup> Emissions from International Bunker Fuels are not included in totals.

<sup>c</sup> HFC-23 emitted

<sup>d</sup> SF<sub>6</sub> emitted

Note: Totals may not sum due to independent rounding.

1-6 and Figure 1-5.

## Methodology and Data Sources

Emissions of greenhouse gases from various sources have been estimated using methodologies that are consistent with the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997). To the extent possible, the present U.S. Inventory relies on published activity and emission factor data. Depending on the emission source category, activity data can include fuel consumption or deliveries, vehicle-miles traveled, raw material processed, etc.; emission factors are factors that relate quantities of emissions to an activity. For some sources, IPCC default methodologies and emission factors have been employed. However, for most emission sources, the IPCC default

methodologies were expanded and more comprehensive methods were applied.

Inventory emission estimates from energy consumption and production activities are based primarily on the latest official fuel consumption data from the Energy Information Administration (EIA) of the U.S. Department of Energy. Emission estimates for NO<sub>x</sub>, CO, and NMVOCs were taken directly, except where noted, from the United States Environmental Protection Agency's (EPA) report, *National Air Pollutant Emission Trends 1900 - 1998* (EPA 1999), which is an annual EPA publication that provides the latest estimates of regional and national emissions of criteria pollutants. Emissions of these pollutants are estimated by the EPA based on statistical information about each source category, emission factors, and control efficiencies. While the EPA's estimation methodologies for criteria pollutants are conceptually similar to the IPCC recommended methodologies, the large number of sources EPA used in developing its criteria pollutant estimates makes it difficult to reproduce the methodologies from EPA (1999) in this inventory document. In these instances, the references containing detailed documentation of the methods used are identified for the interested reader. For agricultural sources, the EPA criteria pollutant emission estimates were supplemented using activity data from other agencies. Complete documentation of the methodologies and data sources used is provided in conjunction with the discussion of each source and in the various annexes.

Emissions from fossil fuels combusted in ships and aircraft engaged in the international transport of passengers and cargo are not included in U.S. totals, but are

Figure 1-5

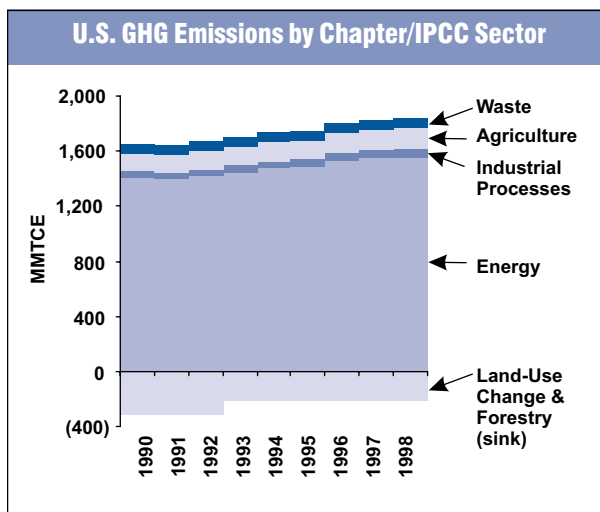


Table 1-6: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMTCE)

Chapter/IPCC Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998
Energy	1,408.4	1,394.5	1,419.4	1,450.2	1,471.1	1,483.0	1,531.5	1,549.5	1,554.8
Industrial Processes	48.3	46.9	48.3	49.5	52.3	57.2	62.5	64.2	66.9
Agriculture	129.0	130.8	133.9	134.3	143.5	141.6	143.9	147.4	147.5
Land-Use Change and Forestry (Sink)*	(316.4)	(316.3)	(316.2)	(212.7)	(212.3)	(211.8)	(211.3)	(211.1)	(210.8)
Waste	64.0	64.1	65.1	65.7	66.0	66.6	66.4	66.7	65.5
<b>Total Emissions</b>	<b>1,649.7</b>	<b>1,636.2</b>	<b>1,666.6</b>	<b>1,699.7</b>	<b>1,733.0</b>	<b>1,748.5</b>	<b>1,804.4</b>	<b>1,827.9</b>	<b>1,834.6</b>
<b>Net Emissions (Sources and Sinks)</b>	<b>1,333.3</b>	<b>1,320.0</b>	<b>1,350.5</b>	<b>1,487.0</b>	<b>1,520.7</b>	<b>1,536.6</b>	<b>1,593.1</b>	<b>1,616.8</b>	<b>1,623.8</b>

\* Sinks are only included in net emissions total. Estimates of net carbon sequestration due to land-use change and forestry activities exclude non-forest soils, and are based partially upon projections of forest carbon stocks.

Note: Totals may not sum due to independent rounding.

reported separately as international bunkers in accordance with IPCC reporting guidelines (IPCC/UNEP/OECD/IEA 1997). Carbon dioxide emissions from fuel combusted within U.S. territories, however, are included in U.S. totals.

## Uncertainty in and Limitations of Emission Estimates

While the current U.S. emissions inventory provides a solid foundation for the development of a more detailed and comprehensive national inventory, it has several strengths and weaknesses.

First, this inventory by itself does not provide a complete picture of past or future emissions in the United States; it only provides an inventory of U.S. emissions for the years 1990 through 1998. However, the United States believes that common and consistent inventories

taken over a period of time can and will contribute to understanding future emission trends. The United States produced its first comprehensive inventory of greenhouse gas emissions and sinks in 1993, and intends to update it annually, in conjunction with its commitments under the UNFCCC. The methodologies used to estimate emissions will also be updated periodically as methods and information improve and as further guidance is received from the IPCC and UNFCCC.

Secondly, there are uncertainties associated with the emission estimates. Some of the current estimates, such as those for CO<sub>2</sub> emissions from energy-related activities and cement processing, are considered to be fairly accurate. For other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated limits the scope or accuracy of the estimates presented. Despite these uncertainties, the *Revised 1996 IPCC Guidelines for National Greenhouse*

### Box 1-2: Greenhouse Gas Emissions from Transportation Activities

Motor vehicle usage is increasing all over the world, including in the United States. Since the 1970s, the number of highway vehicles registered in the United States has increased faster than the overall population, according to the Federal Highway Administration. Likewise, the number of miles driven up 21 percent from 1990 to 1998 and gallons of gasoline consumed each year in the United States have increased relatively steadily since the 1980s, according to the Energy Information Administration. These increases in motor vehicle usage are the result of a confluence of factors including population growth, economic growth, increasing urban sprawl, and low fuel prices.

One of the unintended consequences of these changes is a slowing of progress toward cleaner air in both urban and rural parts of the country. Passenger cars, trucks, motorcycles, and buses emit significant quantities of air pollutants with local, regional, and global effects. Motor vehicles are major sources of carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nonmethane volatile organic compounds (NMVOCs), nitrogen oxides (NO<sub>x</sub>), nitrous oxide (N<sub>2</sub>O), and hydrofluorocarbons (HFCs). Motor vehicles are also important contributors to many serious air pollution problems, including ground-level ozone (i.e., smog), acid rain, fine particulate matter, and global warming. Within the United States and abroad, government agencies have taken strong actions to reduce these emissions. Since the 1970s, the EPA has reduced lead in gasoline, developed strict emission standards for new passenger cars and trucks, directed states to enact comprehensive motor vehicle emission control programs, required inspection and maintenance programs, and more recently, introduced the use of reformulated gasoline to mitigate the air pollution impacts from motor vehicles. New vehicles are now equipped with advanced emissions controls, which are designed to reduce emissions of nitrogen oxides, hydrocarbons, and carbon monoxide.

Table 1-7 summarizes greenhouse gas emissions from all transportation-related activities. Overall, transportation activities excluding international bunker fuels accounted for an almost constant 26 percent of total U.S. greenhouse gas emissions from 1990 to 1998. These emissions were primarily CO<sub>2</sub> from fuel combustion, which increased by 11 percent from 1990 to 1998. However, because of larger increases in N<sub>2</sub>O and HFC emissions during this period, overall emissions from transportation activities actually increased by 12 percent.

**Table 1-7: Transportation-Related Greenhouse Gas Emissions (MMTCE)**

Gas/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
<b>CO<sub>2</sub></b>	<b>399.6</b>	<b>391.5</b>	<b>401.1</b>	<b>409.1</b>	<b>422.3</b>	<b>427.7</b>	<b>441.7</b>	<b>443.4</b>	<b>450.2</b>
Passenger Cars	169.1	167.6	171.7	173.3	172.2	175.0	178.5	180.0	185.1
Light-Duty Trucks	77.4	77.1	77.1	80.4	87.1	88.9	91.1	92.1	94.6
Other Trucks	56.3	54.2	55.9	59.1	62.1	63.6	67.7	70.1	70.3
Buses	2.7	2.8	2.9	3.0	3.3	3.5	3.0	3.2	3.2
Aircraft <sup>a</sup>	48.2	46.1	45.5	45.8	48.0	46.8	49.1	48.8	49.4
Boats and Vessels	15.1	14.4	18.5	17.3	17.0	17.0	18.1	13.7	12.5
Locomotives	7.3	6.8	7.3	6.7	7.9	8.1	8.7	9.0	9.0
Other <sup>b</sup>	23.6	22.3	22.3	23.6	24.8	24.8	25.4	26.5	26.3
International Bunker Fuels <sup>c</sup>	32.2	32.7	30.0	27.2	26.7	27.5	27.9	29.9	31.3
<b>CH<sub>4</sub></b>	<b>1.5</b>	<b>1.5</b>	<b>1.5</b>	<b>1.5</b>	<b>1.5</b>	<b>1.4</b>	<b>1.4</b>	<b>1.4</b>	<b>1.3</b>
Passenger Cars	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.5	0.5
Light-Duty Trucks	0.5	0.5	0.6	0.6	0.6	0.6	0.5	0.5	0.5
Other Trucks and Buses	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Aircraft	+	+	+	+	+	+	+	+	+
Boats and Vessels	+	+	+	+	+	+	+	+	+
Locomotives	+	+	+	+	+	+	+	+	+
Other <sup>d</sup>	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
International Bunker Fuels <sup>c</sup>	+	+	+	+	+	+	+	+	+
<b>N<sub>2</sub>O</b>	<b>13.8</b>	<b>14.6</b>	<b>15.7</b>	<b>16.5</b>	<b>17.1</b>	<b>17.4</b>	<b>17.5</b>	<b>17.3</b>	<b>17.2</b>
Passenger Cars	8.1	8.0	8.4	8.6	8.8	8.9	8.9	8.7	8.6
Light-Duty Trucks	4.2	5.1	5.8	6.4	6.6	6.8	6.8	6.8	6.8
Other Trucks and Buses	0.6	0.7	0.7	0.7	0.8	0.8	0.9	0.9	1.0
Aircraft <sup>d</sup>	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Boats and Vessels	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other <sup>d</sup>	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
International Bunker Fuels <sup>c</sup>	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3
<b>HFCs</b>	<b>+</b>	<b>+</b>	<b>0.2</b>	<b>0.7</b>	<b>1.8</b>	<b>2.6</b>	<b>3.7</b>	<b>4.7</b>	<b>4.7</b>
Mobile Air Conditioners <sup>e</sup>	+	+	0.2	0.7	1.8	2.6	3.7	4.7	4.7
<b>Total<sup>c</sup></b>	<b>414.8</b>	<b>407.5</b>	<b>418.5</b>	<b>427.8</b>	<b>442.7</b>	<b>449.2</b>	<b>464.3</b>	<b>466.8</b>	<b>473.5</b>

+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding.

<sup>a</sup> Aircraft emissions consist of emissions from all jet fuel (less bunker fuels) and aviation gas consumption.<sup>b</sup> "Other" CO<sub>2</sub> emissions include motorcycles, construction equipment, agricultural machinery, pipelines, and lubricants.<sup>c</sup> Emissions from International Bunker Fuels include emissions from both civilian and military activities, but are not included in totals.<sup>d</sup> "Other" CH<sub>4</sub> and N<sub>2</sub>O emissions include motorcycles, construction equipment, agricultural machinery, gasoline-powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel-powered recreational, industrial, lawn and garden, light construction, airport service.<sup>e</sup> Includes primarily HFC-134a**Box 1-3: Greenhouse Gas Emissions from Electric Utilities**

Like transportation, activities related to the generation, transmission, and distribution of electricity in the United States result in significant greenhouse gas emissions. Table 1-8 presents greenhouse gas emissions from electric utility-related activities. Aggregate emissions from electric utilities of all greenhouse gases increased by 15 percent from 1990 to 1998, and accounted for a relatively constant 29 percent of U.S. greenhouse emissions during the same period.<sup>22</sup> The majority of these emissions resulted from the combustion of coal in boilers to produce steam that is passed through a turbine to generate electricity. Overall, the generation of electricity results in a larger portion of total U.S. greenhouse gas emissions than any other activity.

<sup>22</sup> Emissions from nonutility generators are not included in these estimates. Nonutilities were estimated to produce about 10 percent of the electricity generated in the United States in 1998 (DOE and EPA 1999).

**Table 1-8: Electric Utility-Related Greenhouse Gas Emissions (MMTCE)**

Gas/Fuel Type or Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
<b>CO<sub>2</sub></b>	<b>476.6</b>	<b>473.2</b>	<b>472.7</b>	<b>490.5</b>	<b>493.9</b>	<b>494.0</b>	<b>513.0</b>	<b>532.8</b>	<b>549.9</b>
Coal	409.0	407.2	411.8	428.7	429.5	433.0	457.5	471.8	477.3
Natural Gas	41.2	41.1	40.7	39.5	44.0	47.2	40.3	43.6	47.8
Petroleum	26.4	24.9	20.2	22.3	20.5	13.9	15.3	17.5	24.8
Geothermal	0.1	0.1	0.1	0.1	+	+	+	+	+
<b>CH<sub>4</sub></b>	<b>0.1</b>	<b>0.1</b>	<b>0.1</b>	<b>0.1</b>	<b>0.1</b>	<b>0.1</b>	<b>0.1</b>	<b>0.1</b>	<b>0.1</b>
Stationary Combustion (Utilities)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
<b>N<sub>2</sub>O</b>	<b>2.0</b>	<b>2.0</b>	<b>2.0</b>	<b>2.1</b>	<b>2.1</b>	<b>2.1</b>	<b>2.2</b>	<b>2.3</b>	<b>2.3</b>
Stationary Combustion (Utilities)	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.3	2.3
<b>SF<sub>6</sub></b>	<b>5.6</b>	<b>5.9</b>	<b>6.2</b>	<b>6.4</b>	<b>6.7</b>	<b>7.0</b>	<b>7.0</b>	<b>7.0</b>	<b>7.0</b>
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0	7.0	7.0
<b>Total</b>	<b>484.3</b>	<b>481.2</b>	<b>481.0</b>	<b>499.1</b>	<b>502.9</b>	<b>503.2</b>	<b>522.4</b>	<b>542.2</b>	<b>559.3</b>

+ Does not exceed 0.05 MMTCE  
Note: Totals may not sum due to independent rounding. Values do not include emissions from nonutility generators.

*Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) require that countries provide single point estimates for each gas and emission or removal source category. Within the discussion of each emission source, specific factors affecting the accuracy of the estimates are discussed.

Finally, while the IPCC methodologies provided in the *Revised 1996 IPCC Guidelines* represent baseline methodologies for a variety of source categories, many of these methodologies continue to be improved and refined as new research and data becomes available. The current U.S. inventory uses the IPCC methodologies when applicable, and supplements them with other available methodologies and data where possible. The United States realizes that additional efforts are still needed to improve methodologies and data collection procedures. Specific areas requiring further research include:

*Incorporating excluded emission sources.* Quantitative estimates of some of the sources and sinks of greenhouse gas emissions are not available at this time. In particular, emissions from some land-use activities and industrial processes are not included in the inventory either because data are incomplete or because methodologies do not exist for estimating emissions from these source categories. See Annex P for a discussion of the sources of greenhouse gas emissions and sinks excluded from this report.

*Improving the accuracy of emission factors.* Fur-

ther research is needed in some cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources. For example, the accuracy of current emission factors applied to methane and nitrous oxide emissions from stationary and mobile combustion is highly uncertain.

*Collecting detailed activity data.* Although methodologies exist for estimating emissions for some sources, problems arise in obtaining activity data at a level of detail in which aggregate emission factors can be applied. For example, the ability to estimate emissions of methane and nitrous oxide from jet aircraft is limited due to a lack of activity data by aircraft type and number of landing and take-off cycles.

*Applying Global Warming Potentials.* GWP values have several limitations including that they are not applicable to unevenly distributed gases and aerosols such as tropospheric ozone and its precursors. They are also intended to reflect global averages and, therefore, do not account for regional effects. Overall, the main uncertainties in developing GWP values are the estimation of atmospheric lifetimes, assessing indirect effects, choosing the appropriate integration time horizon, and assessing instantaneous radiative forcing effects which are dependent upon existing atmospheric concentrations. According to the IPCC, GWPs typically have an uncertainty of  $\pm 35$  percent (IPCC 1996).

Emissions calculated for the U.S. inventory reflect current best estimates; in some cases, however, estimates are based on approximate methodologies, assumptions, and incomplete data. As new information becomes available in the future, the United States will continue to improve and revise its emission estimates.

## Organization of Report

In accordance with the IPCC guidelines for reporting contained in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997), this U.S. inventory of greenhouse gas emissions and sinks is segregated into six sector-specific chapters, listed below in Table 1-9.

Within each chapter, emissions are identified by the anthropogenic activity that is the source or sink of the greenhouse gas emissions being estimated (e.g., coal mining). Overall, the following organizational structure is consistently applied throughout this report:

— **Chapter/IPCC Sector:** Overview of emission trends for each IPCC defined sector

— **Source:** Description of source pathway and emission trends from 1990 through 1998

— **Methodology:** Description of analytical methods employed to produce emission estimates

— **Data Sources:** Identification of data references, primarily for activity data and emission factors

— **Uncertainty:** Discussion of relevant issues related to the uncertainty in the emission estimates presented

Special attention is given to carbon dioxide from fossil fuel combustion relative to other sources because of its share of emissions relative to other sources and its dominant influence on emission trends. For example, each energy consuming end-use sector (i.e., residential, commercial, industrial, and transportation), as well as the electric utility sector, are treated individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-10.

## Changes in This Year's U.S. Greenhouse Gas Inventory Report

Each year the EPA not only recalculates and revises the emission estimates for all years that are presented in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* but also attempts to improve the analyses themselves through the use of better methods or data. A summary of this year's changes is presented in the following three sections and includes updates to historical data, changes in methodology, and other changes. The magnitude of each change is also described.

Changes to historical data are generally due to statistical data supplied by other agencies. Data sources are provided for further reference.

For methodological changes, differences between

**Table 1-9: IPCC Sector Descriptions**

Chapter/IPCC Sector	Activities Included
Energy	Emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions.
Industrial Processes	By-product or fugitive emissions of greenhouse gases from industrial processes not directly related to energy activities such as fossil fuel combustion.
Solvent Use	Emissions, of primarily non-methane volatile organic compounds (NMVOCs), resulting from the use of solvents.
Agriculture	Anthropogenic emissions from agricultural activities except fuel combustion and sewage emissions, which are addressed under Energy and Waste, respectively.
Land-Use Change and Forestry	Emissions and removals from forest and land-use change activities, primarily carbon dioxide.
Waste	Emissions from waste management activities.

Source: (IPCC/UNEP/OECD/IEA 1997)

**Table 1-10: List of Annexes**

ANNEX A	Methodology for Estimating Emissions of CO <sub>2</sub> from Fossil Fuel Combustion	ANNEX H	Methodology for Estimating Methane Emissions from Enteric Fermentation
ANNEX B	Methodology for Estimating Emissions of CH <sub>4</sub> , N <sub>2</sub> O, and Criteria Pollutants from Stationary Combustion	ANNEX I	Methodology for Estimating Methane Emissions from Manure Management
ANNEX C	Methodology for Estimating Emissions of CH <sub>4</sub> , N <sub>2</sub> O, and Criteria Pollutants from Mobile Combustion	ANNEX J	Methodology for Estimating Methane Emissions from Landfills
ANNEX D	Methodology for Estimating Methane Emissions from Coal Mining	ANNEX K	Global Warming Potential Values
ANNEX E	Methodology for Estimating Methane Emissions from Natural Gas Systems	ANNEX L	Ozone Depleting Substance Emissions
ANNEX F	Methodology for Estimating Methane Emissions from Petroleum Systems	ANNEX M	Sulfur Dioxide Emissions
ANNEX G	Methodology for Estimating Emissions from International Bunker Fuels Used by the U.S. Military	ANNEX N	Complete List of Sources
		ANNEX O	IPCC Reference Approach for Estimating CO <sub>2</sub> Emissions from Fossil Fuel Combustion
		ANNEX P	Sources of Greenhouse Gas Emissions Excluded
		ANNEX Q	Constants, Units, and Conversions
		ANNEX R	Abbreviations
		ANNEX S	Chemical Symbols
		ANNEX T	Glossary

the previous Inventory and this Inventory are explained. Many of the changes in methodology are due to a recent series of IPCC good practice workshops held to assist in the preparation of greenhouse gas inventories and in the implementation of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Unless otherwise noted, the methodological changes incorporated into this year's Inventory reflect the recommendations of experts at these IPCC good practice workshops. In general, when methodological changes have been implemented, the entire time series (1990 through 1998) has been recalculated to reflect the change.

## Changes in Historical Data

- In the CO<sub>2</sub> Emissions from Fossil Fuel Combustion section of the Energy chapter, most differences, as compared to previous emission estimates, are due to revised energy consumption data from the Energy Information Administration (EIA 1999a, 1999c, 1999d) for selected years (see below for detail on an additional small methodological change). In addition, a small error in estimates of CO<sub>2</sub> emissions from combustion of petroleum used for transportation has been corrected in this Inventory. Previously, the combustion efficiency had been inadvertently applied to bunker fuel emissions prior to removing them from the calculation of CO<sub>2</sub> emissions from petroleum used for transportation. In the current Inventory, the combustion efficiency is correctly

applied once to all emissions after the subtraction of bunker fuels. The combined data and methodological changes resulted in an average decrease of 4.3 MMTCE (0.3 percent) in annual CO<sub>2</sub> emissions from fossil fuel combustion for 1990 through 1997.

- In the Stationary Combustion (excluding CO<sub>2</sub>) section of the Energy Chapter, differences from previous emission estimates are due to revised energy consumption data from the EIA (1999a, 1999d) for selected years. This revision resulted in an increase of less than 0.1 MMTCE (0.6 percent) in annual CH<sub>4</sub> emissions and an average increase of less than 0.1 MMTCE (0.7 percent) in annual N<sub>2</sub>O emissions from stationary combustion for 1990 through 1997.
- In the Mobile Combustion (excluding CO<sub>2</sub>) section of the Energy Chapter, differences with previous emission estimates for highway sources are due to revised estimates of historical vehicle-miles-traveled by the Federal Highway Administration (FHWA 1999). Extremely small differences exist in the non-highway estimates due to revised historical fuel consumption data from EIA (1999a, 1999c) and FHWA (1999). These revisions caused an average increase of less than 0.1 MMTCE (3.0 percent) in annual CH<sub>4</sub> emissions and an increase of 0.3 MMTCE (1.9 percent) in annual N<sub>2</sub>O emissions from mobile combustion for 1990 through 1997.
- In the Natural Gas Systems section of the Energy

Chapter, historical estimates of methane emissions are revised based on the transmission pipeline mileage reported by the Office of Pipeline Safety (OPS). Inventories in previous years relied on the American Gas Association (AGA) for transmission pipeline mileage data. AGA aggregates pipeline mileage data as reported in FERC Form 2 “Annual Report of Natural Gas Pipeline Companies”; however, only interstate pipeline companies regulated by FERC submit Form 2. In contrast, OPS data is for all companies with more than one mile of transmission pipeline and includes both intra- and interstate pipelines. Accordingly, OPS reports pipeline mileage that is higher than that reported by AGA. Using the new data, EPA recalculated historical emission estimates, which resulted in increases for most years. The historical emission estimates have increased an average of 0.7 MMTCE (1.5 percent) in annual CH<sub>4</sub> emissions for 1990 through 1997.

- In the Natural Gas Flaring and Criteria Pollutant Emissions in the Oil and Gas Activities section of the Energy chapter, changes in emission estimates for natural gas flaring are due to revisions in data from the EIA (1999e). These revisions caused an average increase of 0.2 MMTCE (5.8 percent) in CO<sub>2</sub> annual emissions for 1990 through 1997. The EPA (1999b) has also revised estimates for criteria pollutants from oil and gas activities for 1996 and 1997. These revisions resulted in average increases of 3.5 percent in annual NO<sub>x</sub> emissions, and 3.9 percent in CO annual emissions from 1990 through 1997, and 1.0 percent in annual NMVOCs emissions from 1990 through 1997.
- In the International Bunker Fuels section of the Energy chapter, a small error in the 1990-1997 Inventory is corrected in this volume. Emissions from combustion of distillate fuel in marine bunkers were misreported by two years in that edition, presenting 1988 estimates for 1990, 1989 estimates for 1991, and so forth. In addition, the activity data for foreign airlines at U.S. airports in 1997 have been adjusted slightly (BEA 1999). The combined data and methodological changes resulted in an average decreases of 2.0 MMTCE (7.4 percent) in annual CO<sub>2</sub>

emissions, less than 0.1 MMTCE (10.9 percent) in annual CH<sub>4</sub> emissions and less than 0.1 MMTCE (8.3 percent) in annual N<sub>2</sub>O emissions from international bunker fuels for 1990 through 1997.

- In the Limestone and Dolomite Use section of the Industrial Processes chapter, the 1997 value for limestone and dolomite consumption was revised by the United States Geological Survey (USGS 1999). This data change resulted in an increase of 0.2 MMTCE, or 9.3 percent, of CO<sub>2</sub> emissions from limestone and dolomite use in 1997.
- In the Carbon Dioxide Consumption section of the Industrial Processes chapter, the 1997 value was revised. The reference (Freedonia 1999) does not provide data for 1997, so it has been extrapolated using annual growth rates from confirmed 1993 through 1996 values. Previously, the growth in CO<sub>2</sub> production was also applied to calculate CO<sub>2</sub> used in EOR applications. However, this year’s data shows that Freedonia holds EOR constant for 1996-1998. This revision in data resulted in an average increase of less than 0.1 MMTCE, or 5.3 percent, of CO<sub>2</sub> emissions from CO<sub>2</sub> consumption for 1997.
- In the Petrochemical Production section of the Industrial Processes chapter, the differences between the 1990-1997 Inventory and this volume reflect updated production data for ethylene, ethylene dichloride, and methanol from the Chemical Manufacturers Association (CMA 1999). These updates caused an average increase of less than 0.1 MMTCE (1.5 percent) in annual CH<sub>4</sub> emissions from petrochemical production for 1994 through 1997.
- In the Substitution of Ozone Depleting Substances section of the Industrial Processes chapter, a review of the current chemical substitution trends with input from industry representatives resulted in updated assumptions for the Vintaging Model, particularly in the stationary refrigeration and foams sectors. These updates resulted in an average decrease of 2.0 MMTCE (22.7 percent) in aggregate HFC, PFC, and SF<sub>6</sub> emissions from substitution of ozone depleting substances for 1994 through 1997.
- In the Enteric Fermentation section of the Agriculture chapter, the emission estimates for the 1990-

1998 Inventory have been recalculated using updated animal population data. Specifically, animal population data for 1994 through 1997 were updated to reflect the recent publication of final livestock population estimates by USDA (1999a-h, n). Also, horse population data for 1990 through 1998 were updated to reflect revised data from the Food and Agriculture Organization (FAO 1999). The dairy cow emission factors were also updated to reflect revised milk production data. These data modifications caused an average increase of less than 0.1 MMTCE (less than 0.1 percent) in annual CH<sub>4</sub> emissions from enteric fermentation for 1990 through 1997.

## Methodological Changes

### Carbon Dioxide Emissions from Fossil Fuel Combustion

The emission factor used to calculate emissions from the combustion of residual fuel at electric utilities was updated to 21.29 MMTCE/QBtu, based on new data that EIA received from electric utilities (EIA 1999b). The emission factor for residual fuel for all other sectors remains at 21.49 MMTCE/QBtu.

Additionally, non-bunker jet fuel emissions from military vehicles for 1990-1998, which are accounted for under the transportation end-use sector, have been estimated for the first time in this inventory. Data on jet fuel expenditures by the U.S. military was supplied by the Office of the Under Secretary of Defense (Environmental Security), U.S. Department of Defense (DoD). Data on fuel delivered to the military within the U.S. was provided from unpublished data by the Defense Energy Support Center, under DoD's Defense Logistics Agency. The quantity of fuel used was estimated using these data sources. Jet fuel densities for each fuel type were obtained from the Air Force (1998). The combined data and methodological changes resulted in an average decrease of 4.3 MMTCE (0.3 percent) of CO<sub>2</sub> annual emissions from fossil fuel combustion for 1990 through 1997.

### Petroleum Systems

EPA has restated the emissions of methane from petroleum systems for 1998 and previous years, resulting in a substantial, 5.4 MMTCE, almost four-fold increase in the estimate in CH<sub>4</sub> from 1990 through 1997. The new, higher estimate of methane emissions from petroleum systems is based on work sponsored by EPA and presented in *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999a). Where the previous estimates of methane emissions from the petroleum industry used emission and activity factors based on top-down, broad categories of activities, the revised approach is based on a more detailed, bottom-up analysis of 70 different crude oil handling and processing activities from the wellhead to refining.

The overall approach to these new petroleum sector estimates is now consistent with the detailed, bottom-up analysis that has been used for several years to estimate methane emissions from the natural gas industry. As with natural gas, the new approach to estimating methane emissions from petroleum systems is based on a detailed characterization of the petroleum sector, which describe the emissions producing sources within the sector. Under this approach, EPA has developed emissions factors for each emission producing activity that describes the rate of annual emissions per activity. The emissions factors derive largely from Radian International LLC (Radian 1996e). Other sources of emissions factors include data from various reports and documents of the American Petroleum Institute, EPA, Minerals Management Service (MMS) reports, Gas Research Institute (GRI), Canadian Association of Petroleum Producers (CAPP), and various industry peer review panels. Activity factors are used to generalize the emissions to the entire industry and are multiplied by the emission factors to generate the total emissions estimates. The major sources of activity factors include various reports from the Energy Information Administration (EIA), API, Radian, EPA, MMS, the *Oil & Gas Journal*, and peer review panels.

### International Bunker Fuels

International bunker fuel emissions resulting from military aviation and marine activities for 1990-1998 have been estimated for the first time in this inventory. Data on jet fuel expenditures by the U.S. military was supplied by the Office of the Under Secretary of Defense (Environmental Security), U.S. Department of Defense (DoD). Estimates of the percentage of each services' total operations that are international operations were developed by DoD. Military aviation bunkers include international operations, operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea. Data on fuel delivered to the military within the U.S. was provided from unpublished data by the Defense Energy Support Center, under DoD's Defense Logistics Agency. Together, the data allow the quantity of fuel used in military international operations to be estimated. Jet fuel densities for each fuel type were obtained (Air Force 1998). The combined data and methodological changes resulted in an average decreases of 2.0 MMTCE (7.4 percent) in annual CO<sub>2</sub> emissions, less than 0.1 MMTCE (10.9 percent) in annual CH<sub>4</sub> emissions and less than 0.1 MMTCE (8.3 percent) in annual N<sub>2</sub>O emissions from international bunker fuels for 1990 through 1997.

### Cement Manufacture

During clinker production some of the clinker precursor materials remain in the kiln as non-calcinated, partially calcinated, or fully calcinated cement kiln dust. The emissions attributable to the calcinated portion of the cement kiln dust are not accounted for by the clinker emission factor. These additional CO<sub>2</sub> emissions were estimated as 2 percent of the CO<sub>2</sub> emissions calculated from clinker production. The previous inventory did not include cement kiln dust emissions estimates. These additional emissions from cement kiln dust were combined with the emissions from clinker production to calculate total cement production emissions. This methodological change resulted in an average increase of 0.2 MMTCE (2.0 percent) in annual CO<sub>2</sub> emissions from cement manufacture for 1990 through 1997.

### Lime Manufacture

During the calcination stage of lime manufacture, CO<sub>2</sub> is driven off as a gas and normally exits the system with the stack gas. Carbon dioxide emissions were estimated by applying a CO<sub>2</sub> emission factor to the total amount of lime produced. The emission factor used in this analysis is the product of the mass of CO<sub>2</sub> released per unit of lime, and the average calcium plus magnesium oxide (CaO + MgO) content of lime. In previous inventories the average calcium plus magnesium oxide content of lime was not factored into the emissions factor. The inclusion of the CaO or CaO + MgO content of lime in the current inventory, was recommended by the National Lime Association (Males 1999). Lime industry experts believe that approximately 93 percent is a representative value for lime's average calcium plus magnesium oxide content (ASTM 1996; Schwarzkopf 1995). The remainder is composed of silica, aluminum, and iron oxides (3.83 percent) and CaCO<sub>3</sub> (3.41 percent). These other compounds are present because limestone feed is not 100 percent pure, nor is the conversion process 100 percent efficient (Males 1999). This yields an emission factor of 0.73 tons of CO<sub>2</sub> per ton of lime produced. In the previous Inventory, CaO was considered to be 100 percent of limestone, thus yielding an emission factor of 0.785 tons of CO<sub>2</sub> per ton of lime produced. This methodological change resulted in an average decrease of 0.2 MMTCE (6.8 percent) in annual CO<sub>2</sub> emissions from lime manufacture for 1990 through 1997.

### Adipic Acid Production

The equation used to estimate N<sub>2</sub>O emissions from adipic acid production was changed from the previous Inventory to include both a destruction factor and an abatement system utilization factor. The N<sub>2</sub>O destruction factor represents the amount of N<sub>2</sub>O expressed as a percentage of N<sub>2</sub>O emissions that are destroyed by the currently installed abatement technology. The abatement system utilization factor represents the percent of time that the abatement equipment operates. This methodological change resulted in an average increase of 0.3 MMTCE (7.5 percent) in annual N<sub>2</sub>O emissions from

adipic acid production for 1990 through 1997.

### Nitric Acid Production

An estimated 20 percent of nitric acid plants in the United States are equipped with Non-Selective Catalytic Reduction (NSCR) technology (Choe, et al. 1993). In the process of destroying NO<sub>x</sub>, NSCR systems also destroy 80 to 90 percent of the N<sub>2</sub>O. Hence, the emission factor is equal to  $(9.5 \times 0.80) + (2 \times 0.20) = 8$  kg N<sub>2</sub>O per metric ton HNO<sub>3</sub>. In previous Inventories the emission factor was calculated without weighting the percent of plants using NSCR and Selective Catalytic reduction (SCR) technologies, thus the previous emission factor was 5.5 kg N<sub>2</sub>O per metric ton HNO<sub>3</sub>. This methodological change resulted in an average increase of 1.7 MMTCE (46.2 percent) in annual N<sub>2</sub>O emissions from nitric acid production for 1990 through 1997.

### Aluminum Production

PFC emissions from aluminum production were estimated by multiplying an emission factor by the annual production. In the previous Inventory, PFC emissions were estimated using a single per unit emission factor for 1990, and emissions for 1991 through 1996 were estimated with emission factors that incorporated data on reductions in anode effects provided by aluminum companies through the Voluntary Aluminum Industry Partnership (VAIP). The current inventory combines data on smelter operating parameters (anode effect frequency and anode effect duration) with slope coefficients that relate the operating parameters to emissions of CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub>. The operating parameter data has been reported by smelters and the slope coefficients are based upon measurements taken at the individual smelters. In cases where data reports or smelter specific coefficients are unavailable, technology-specific defaults have been used. These revisions in methodology resulted in an average increase of 0.3 MMTCE (8.3 percent) in annual PFC emissions from aluminum production for 1990 through 1997.

### Semiconductor Manufacture

HFC, PFC, and SF<sub>6</sub> emissions from semiconductor

manufacture were estimated using silicon chip manufacturing characteristics and data provided through the Emission Reduction Partnership for the Semiconductor Industry. For previous Inventories, emissions were estimated based on gas sales data from 1994, emission factors for the most commonly used gases, and projections regarding the growth of semiconductor sales and the effectiveness of emission reduction efforts. For the 1998 Inventory, emissions have been recalculated using an improved estimation method that uses two sets of data. For 1990 through 1994, emissions were estimated based on the historical consumption of silicon (square centimeters), the estimated average number of interconnecting layers in the chips produced, and an estimated per-layer emission factor. The average number of layers per chip was based on industry estimates of silicon consumption by line-width and of the number of layers per line-width. The per-layer emission factor was based on the total annual emissions reported by the participants in the EPA's Emission Reduction Partnership for the Semiconductor Industry. For the three years for which gas sales data were available (1992 through 1994), the estimates derived using the new method are within 10 percent of the estimates derived using gas sales data and average values for emission factors and GWP values.

For 1995 through 1998, emissions were estimated based on the total annual emissions reported by the participants in the EPA's Emission Reduction Partnership for the Semiconductor Industry. Partners estimate their emissions using a range of methods; the partners with relatively high emissions typically multiply estimates of their PFC consumption by process-specific emission factors that they have either measured or obtained from suppliers manufacturing equipment and based tools. To estimate total U.S. emissions from semiconductor manufacturing based on reported partner emissions, a per-plant emissions factor was estimated for the partners. This per-plant emission factor was then applied to plants operated by semiconductor manufacturers who were not partners, considering the varying characteristics of the plants operated by partners and non-partners (e.g., typi-

cal plant size and type of device produced). The resulting estimate of non-partner emissions was added to the emissions reported by the partners to obtain total U.S. emissions. These revisions in methodology resulted in an average increase of 0.4 MMTCE (72.4 percent) in annual HFC, PFC, and SF<sub>6</sub> emissions from semiconductor manufacture for 1990 through 1997.

### **Manure Management**

The methodology for estimating N<sub>2</sub>O emissions from manure management no longer assumes that 20 percent of the manure nitrogen volatilizes before N<sub>2</sub>O production and therefore is not available for N<sub>2</sub>O production. This assumption was used in previous Inventories to correct for what appeared to be an inconsistency with the Agricultural Soil Management emission estimate methodologies, which account for indirect N<sub>2</sub>O emissions from nitrogen volatilized from managed manure systems, as well as from nitrogen in applied animal manure. However, as a result of efforts carried out by the IPCC in their work on inventory “good practice,” the determination was made that there is not an inconsistency. Through this process, it became clear that the total amount of manure nitrogen in managed systems is available for both N<sub>2</sub>O production (accounted for in the Manure Management calculations) and nitrogen volatilization (accounted for in the Agricultural Soil Management calculations). Therefore, this step has been removed so that the methodology corresponds with the guidance described in IPCC/UNEP/OECD/IEA (1997). This results in a larger amount of nitrogen available for N<sub>2</sub>O production.

Additionally, all animal population data, except horses, for 1994 through 1997 were updated to reflect the recent publication of final livestock population estimates for 1994 through 1997 from USDA (USDA 1999a-f, i-o). Horse population data for 1990 through 1998 were updated to reflect updated data from the Food and Agriculture Organization (FAO 1999). These methodological and data changes together cause an average increase of 1.9 MMTCE (11.2 percent) in annual CH<sub>4</sub> emissions and 0.8 MMTCE (28.3 percent) in annual N<sub>2</sub>O emissions from manure management for 1990

through 1997.

### **Rice Cultivation**

The climatic conditions of Arkansas (in 1998), southwest Louisiana, Texas, and Florida allow for a second, or ratoon, rice crop to be grown each year. This second rice crop is produced from re-growth on the stubble after the first crop has been harvested. For the 1990-1998 U.S. Inventory, the approach used to estimate emissions from rice cultivation was modified to account for emissions from ratooned and primary areas separately. In this Inventory, data was collected on the flooding season length, area cultivated, and emissions rate range for both the primary and ratoon crops. In previous Inventories, emissions from the primary and ratoon seasons were not estimated separately. Instead, flooding season lengths and a daily emission factor range that are representative of the primary crop were used to estimate emissions from both the primary and ratooned areas. This approach was assumed to result in a reasonable first approximation for the ratooned areas because the higher daily average emissions from ratooned areas are at least somewhat canceled out by a shorter ratoon flooding season (compared to the primary crop). For the current Inventory, information on ratoon flooding season lengths was collected from agricultural extension agents in the states that practice ratooning, and emission factors for both the primary season and the ratoon season were derived from published results of field experiments in the United States. This change caused an average decrease of 0.2 MMTCE (6.3 percent) in annual CH<sub>4</sub> emissions from rice cultivation for 1990 through 1997.

### **Agricultural Soil Management**

The current Inventory includes two new sources of nitrogen that were not accounted for in previous inventories: land application of sewage sludge and production of non-alfalfa forage legumes. The current Inventory also includes several data and methodological changes relative to the previous Inventory. Three changes to the data have been made. First, an error was found in a conversion factor used to calculate organic fertilizer nitrogen consumption; correcting this factor has resulted

in higher organic fertilizer consumption statistics and lower synthetic fertilizer consumption statistics. Second, crop production statistics for some crops have changed due to the use of updated statistics from the U.S. Department of Agriculture (USDA 1994a, 1998). Third, a more recent data source has been used to estimate the annual areas under histosol cultivation, resulting in higher area estimates for the entire time series (USDA 1994b).

Two methodological changes have also been made. First, the emission factor for histosol cultivation has been revised upward as a result of new guidance proposed by the IPCC in their work on inventory “good practice.” Second, in the indirect calculations for leaching and runoff, the total amount of applied nitrogen has been assumed to be subject to leaching and runoff, rather than just the unvolatilized portion. This change was also a result of work carried out under the “good practice” inventory effort. Through this process, it became clear that the methodology assumes all of the volatilized nitrogen redeposits. Therefore, in order to simplify the methodology, rather than including a volatilization and subsequent redeposition step, the leaching and runoff fraction is just applied to all the applied nitrogen in a single calculation. This change to the leaching and runoff calculation has resulted in an increase in the emission estimates for this process. All the changes taken together (i.e., the inclusion of the two additional sources of applied nitrogen, combined with the data changes and the methodological changes) resulted in an average increase in the annual emissions from agricultural soil management of 10.2 MMTCE (14.7 percent) relative to the estimates in the previous Inventory.

### **Agriculture Residue Burning**

This inventory includes three methodological changes as compared to previous Inventories. Previous calculations on rice production in Florida were based on the assumption that the Sem-Chi Rice Co. accounted for all of Florida’s rice production. However, this Inventory uses revised production data to include acreage from additional producers. Average production per acre for Florida for all years was assumed to be the same as 1998

productivity of Sem-Chi Rice. Total production in Florida for 1990 through 1998 was estimated using this average productivity and the revised annual acreage.

The methodology for estimating the percentage of rice crop residue burned from rice was also revised. In the previous Inventory, the percentage of rice burned was assumed to be 3 percent in all states except California. To obtain a more accurate estimate for this Inventory, estimates of the percentage of rice area burned per year for 1990 through 1998 in each of the seven rice burning states were obtained from agricultural extension agents. A weighted (by area) national average percent area burned was calculated for each year.

Additionally, production numbers for corn were changed to include only corn from grain. Corn for silage was included in the previous Inventory, but is now excluded because there is no resulting residue. Historical crop production data, which previously had been taken from annual USDA summary reports, was revised using two USDA reports of final crop estimates (USDA 1994a, 1998). These methodological changes cause an average decrease of less than 0.1 MMTCE (17.1 percent) in annual CH<sub>4</sub> emissions and less than 0.1 MMTCE (12.9 percent) in annual N<sub>2</sub>O emissions from agriculture residue burning for 1990 through 1997.

### **Landfills**

The methodology used to estimate recovered landfill gas was altered from the previous Inventory. Previous landfill gas recovery estimates (1990-1997) were based on 1990 and 1992 data obtained from Governmental Advisory Associates (GAA 1994). The 1998 Inventory reflects estimates of landfill gas recovered per year based on site-specific data collected from vendors of flaring equipment, and a database on landfill gas-to-energy (LFGTE) projects compiled by the EPA’s Landfill Methane Outreach Program (LMOP). Based on the information provided by vendors, the EPA estimated total methane recovered due to the use of 235 flares for 1990 through 1998. This estimate likely underestimates emissions because the EPA believes that more than 700 flares are in use at landfills in the United States. The

EPA is currently working with the Solid Waste Association of North America (SWANA) to better characterize the emissions reduced by flaring and expects to present a revised estimate in the next Inventory. Additionally, the LMOP database provided data on landfill gas flow and energy generation for 237 out of approximately 260 operational LFGTE projects. From this data, the EPA was able to estimate the methane emissions avoided due to LFGTE projects.

The EPA assumes that emissions from industrial landfills are equal to seven percent of the total methane emissions from municipal landfills. The amount of methane oxidized is assumed to be ten percent of the methane generated (Liptay et al. 1998). To calculate net methane emissions, methane recovered and oxidized is subtracted from methane generated at municipal and industrial landfills. The 1990 through 1997 emission estimates were updated for this Inventory according to the revised recovery estimates. This change resulted in an average decrease in the annual estimates of total CH<sub>4</sub> emissions from landfills of 1.6 MMTCE (2.3 percent) relative to the estimates in the previous Inventory.

### Human Sewage

The assumptions used to estimate N<sub>2</sub>O emissions from human sewage changed slightly from those used for the previous Inventory. The total estimate of nitrogen in human sewage was decreased by the amount of nitrogen added to soils via sewage sludge applications which are accounted for under the Agricultural Soil Management source category.

Annually variable population and per capita protein consumption factors were obtained from the U.S. Census Bureau and the United Nations Food and Agriculture Organization (FAO), respectively. Protein consumption estimates are updated by the FAO annually. However, data for protein intake was unavailable for 1998

and therefore, the value of per capita protein consumption for the previous year was used. In addition, the protein intake estimate for 1997 was unavailable for the 1997 Inventory. Thus, this Inventory reflects an updated 1997 protein intake estimate published in 1998. These methodological changes for the 1990 through 1997 estimates resulted in an average annual decrease in N<sub>2</sub>O emissions from Human Sewage of 0.2 MMTCE (6.8 percent) relative to the estimates in the previous Inventory.

## Other Changes

Two source categories have been added in the current Inventory. First, CO<sub>2</sub> emissions from the combustion of plastics in municipal solid waste are now reported in the Waste Combustion section. Previously, only N<sub>2</sub>O emissions had been estimated. The second, an addition in Land-Use Change and Forestry, addresses the storage of carbon resulting from the disposal of yard trimmings in landfills. Yard trimmings, a sizeable portion of municipal solid waste, are a significant carbon sink when landfilled.

The IPCC Reporting Tables, presented in Annex N of the 1990-1997 Inventory, have been removed from this Inventory. A new, more detailed, common reporting format has been developed by the UNFCCC as a substitute for those tables. The United States intends to submit information to the UNFCCC Secretariat using this common reporting format in a separate report.

